

GRB Explosion in a Galactic Supershell : GRB 971214^a

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Among a number of gamma-ray bursts whose host galaxies are known, GRB971214 stands out for its high redshift ($z = 3.25$) and the $\text{Ly}\alpha$ emission line having a P-Cygni type profile. which is interpreted to be a direct consequence of the expanding supershell. From a simple Voigt-fitting analysis, we estimate the expansion velocity of the supershell and the neutral column density. The theory on the evolution of supernova remnants is used to propose that the supershell is at the adiabatic phase, with its radius $R = 10E_{53}^{1/2}$ pc, its age $t = 4.7 \times 10^3 E_{53}^{1/2}$ yrs, and the density of the ambient medium $n_1 = 5.4E_{53}^{-1/2} \text{ cm}^{-3}$, where $E_{53} = E/10^{53}$ ergs. I estimate the kinetic energy of the supershell to be $E_k = 7.3 \times 10^{52} E_{53}$ ergs. I provide an observational evidence that the gamma-ray burst can occur in a giant H II region whose environment is similar to that in star-forming galaxies.

1 Motivation

Gamma ray bursts (hereafter GRBs), located at cosmological distances, form a group of the most luminous objects in the Universe. A number of GRBs were observed with their host galaxies, of which intensive spectroscopic and imaging observations have been performed using the Hubble Space Telescope and the Keck telescopes.

GRB971214 is one of such objects with a very high redshift $z > 3$ and also is worth a particular attention in following points.

Firstly, even after the optical transient region had faded away, we can marginally detect a bright spot in the *HST* image, and the continuum and emission line fluxes from this spot overwhelm those from the remaining part of the host galaxy. Secondly, the ultraviolet spectrum of GRB971214 illustrated in Figure 7.1 shows a flat UV continuum which is often found in star forming galaxies. In addition, the $\text{Ly}\alpha$ emission line has a black absorption trough in the red part of the emission peak. These facts imply that the UV spectrum is formed in a star forming region which is surrounded by a thick and expanding medium of neutral hydrogens. We note that the location of the GRB afterglow coincides with the star forming region or the bright spot, which leads to the proposal that the GRB occurs in a star forming region, and in this Letter we deduce the physical environment of the GRB from its spectrum.

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The P-Cygni type Ly α emission in the spectrum of primeval galaxies has been often attributed to an absorption effect by a galaxy not associated with the primeval galaxy but intervening accidentally in the line of sight. It has been regarded as a damped Ly α absorption that occurs in the vicinity of the source galaxy. In order to check this possibility, we calculate the probability for observing an intervening galaxy in front of the GRB host galaxy, which is none other than the optical depth for seeing a galaxy between the GRB host galaxy at $z = 3.425$ and the place that corresponds to v_{exp} in the Hubble's expansion law. The optical depth is simply expressed by

$$\tau = n_g(1+z)^3 \sigma L, \quad (1)$$

where the comoving volume number density of normal galaxies at $z = 0$, $n_g \sim 0.02 h^3 \text{Mpc}^{-3}$ (Im 1995), and the path length L is estimated to be $L = v_{\text{exp}}/H$ with H being the Hubble constant at the redshift and given by

$$H = H_0[\Omega_M(1+z)^3 + \Omega_\Lambda]^{1/2}, \quad (2)$$

where the cosmological density parameters are $\Omega_M = 8\pi G\rho_0/3H_0^2$, $\Omega_\Lambda = \Lambda/3H_0^2$, and the Hubble parameter $H_0 = 65 \text{km s}^{-1} \text{Mpc}^{-1}$. Here, the cross section is given by $\sigma = \pi(r_{10}10h^{-1}\text{kpc})^2$, where r_{10} is the typical galaxy size in units of 10kpc. A direct substitution yields the optical depth $\tau = 0.0023r_{10}^2$ for $\Omega_M = 1/3$ and $\Omega_\Lambda = 2/3$, and $\tau = 0.0025r_{10}^2$ for $\Omega_M = 0.3$ and $\Omega_\Lambda = 0$. This indicates that if the average size of galaxies at $z \approx 3$ is not large, then it is highly improbable that the damped absorption in the spectrum of host galaxy of GRB971214 is formed by a galaxy intervening accidentally.

This leaves us to consider an alternative hypothesis, according to which the P-Cygni type profile of Ly α is formed by the the expanding supershell that surrounds the star forming region in GRB971214 and is the remnant of the GRB precedent to GRB971214. In order to check this possibility, we now calculate a number of GRB event in a galaxy at $z \simeq 3.4$. Assuming the supernova rate is proportional to the star-forming rate, Sadat et al. (1998) calculated the supernova rate at $z \approx 3.4$, $\Gamma_{SN} \simeq 0.011 \times 10^6 h_{65}^3 \text{SNeMyr}^{-1} \text{Mpc}^{-3}$, where $H_0 = 65 h_{65} \text{km s}^{-1} \text{Mpc}^{-1}$. Accepting the concept that the GRB rate traces the massive star formation rate, Woods & Loeb (1998) showed $\Gamma_{GRB} \simeq 10^{-6} \Gamma_{SN}$, where $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 65 h_{65} \text{km s}^{-1} \text{Mpc}^{-1}$. Therefore, $\Gamma_{GRB}(z \approx 3.4) \simeq 0.011 h_{65}^3 \text{Myr}^{-1} \text{Mpc}^{-3}$. Adopting the number density of galaxies at $2.0 < z < 3.5$, $\Phi^* = 1.76 \times 10^{-3} h_{65}^3 \text{Mpc}^{-3}$ (Pozzetti et al. 1998), we can get the GRB rate per a galaxy at $z \approx 3.4$, $\Gamma_{GRB} \simeq 6 \text{Myr}^{-1}$. Therefore, the number of GRB events per a galaxy during 10^4 yrs is $N_{GRB} = 0.06$. Moreover, the beaming factor, if exists, can increase the event rate by another factor

of ten to hundred and the number of GRB events per a galaxy during 10^4 yrs is $N_{GRB} \approx 0.6 - 6$, which makes our supershell hypothesis more probable and alternative suggestion.

In this talk, we adopt the hypothesis of GRB-driven supershell and perform a profile fitting analysis to derive physical parameters characterizing the expanding supershell of neutral hydrogens surrounding the star forming region of the GRB host galaxy.

2 Images and Spectrum of GRB971214

GRB971214 was detected at 9 UT, December 14, 1997 (Heise et al. 1997), and its optical counterpart twelve hours after the burst (Halpern et al. 1998). With a total fluence of 1.09×10^{-5} ergs cm^{-2} (Kippen et al. 1997) and the measured redshift of $z = 3.418$ (Kulkarni et al. 1998), its energy release is estimated to be $\sim 3 \times 10^{53}$ ergs in γ -rays alone under the assumption of isotropic emission, $\Omega_0 = 0.3$, and $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

In Figure 1 is shown its ultraviolet spectrum redshifted to the optical band and obtained by Kulkarni et al. (1998) using the Keck telescope. It is characterized by a flat UV continuum that is typically found in the spectra of star forming regions. It is also seen that the $\text{Ly}\alpha$ emission has a P-Cygni type profile, which is frequently observed in the astronomical objects near or far (Lee & Ahn 1998). Lee and Ahn (1998) proposed that the P-Cygni type $\text{Ly}\alpha$ line is formed when the $\text{Ly}\alpha$ photons emitted in the central super star-cluster are radiatively transferred in a HI supershell that are optically thick and expanding. Hence, we assume that the photon source is the H II region that may contain 10^4 O stars. According to Marlowe et al. (1995), nearby starbursting dwarfs are inferred to contain a similar number of OB stars, when considering H α luminosity. So this can be thought to be neither entirely new nor extreme assumption for galaxies of higher redshifts. Furthermore, it appears less plausible that the $\text{Ly}\alpha$ emission arises from the medium ionized by shocks produced by supernovae or hypernovae. This is because the number density of the inner region is not sufficiently high to give the recombination time scale $\leq 10^5$ years.

3 Is the Photon Source Surrounded by the GRB Remnant?

3.1 Interpretation of the P-Cygni Absorption

In this work we will consider the shell hypothesis, and derive the physical properties of the expanding neutral medium from the observed $\text{Ly}\alpha$ absorption.

We assume a Gaussian profile for the unobscured Ly α emission and convolve it with a Voigt function with the center displaced by the expanding velocity that will be determined by the fitting procedure. In principle, the effect of the frequency redistribution by back-scatterings should be considered. However, we neglect this effect in this paper, because the S/N ratio and the resolution of the spectrum are not sufficiently good. For the continuum level, the blue part of Ly α , which is more prone to extinction, is extrapolated from the red portion of the spectrum given by Kulkarni et al. (1998). They quote $F_\nu = 174(\nu/\nu_R)^\alpha$ nJy with $\alpha = -0.7 \pm 0.2$, where F_ν is the spectral density at frequency ν and $\nu_R = 4.7 \times 10^{14}$ Hz, the central frequency of the R band.

We show the result in Figure 1, where the dotted line represents the best fit profile, the solid line the observed profile, and the horizontal solid line the continuum level. The best fit expansion velocity of the supershell relative to the H II region is determined to be $v_{\text{exp}} = 1500$ km s $^{-1}$, and the best fit line center optical depth $\tau_0 = 6 \times 10^6$, which corresponds to $N_{\text{HI}} = 10^{20}$ cm $^{-2}$. The best fit Ly α profile has the width of $\sigma = 5$ Å and the line center flux $f(\lambda = 5280.8 \text{ Å}) = 0.675$ μ Jy, which gives the unobscured flux to be 9.1×10^{-18} erg cm $^{-2}$ s $^{-1}$ and the systemic redshift $z = 3.425$.

Assuming a standard Friedman cosmology with $H_0 = 65$ km s $^{-1}$ Mpc $^{-1}$ and $\Omega_0 = 0.3$, the luminosity distance $d_L = 9.7 \times 10^{28}$ cm. Considering the Galactic extinction, the unobscured Ly α flux is corrected to be $F_{\text{Ly}\alpha} = (1.5 \pm 0.7) \times 10^{-17}$ erg cm $^{-2}$ s $^{-1}$, where the observational error given by Kulkarni et al. (1998) is introduced. Therefore, for the assumed cosmology, the Ly α line luminosity $L_{\text{Ly}\alpha} = (1.8 \pm 0.8) \times 10^{42}$ erg s $^{-1}$. If there is no internal extinction in the interior of the Ly α source, this corresponds to $n_e = (1.4 \pm 0.4)(\frac{L}{L_{\text{Ly}\alpha}})^{0.5}(\frac{R}{1 \text{ kpc}})^{-1.5}$ cm $^{-3}$ or $n_e = (40 \pm 10)(\frac{L}{L_{\text{Ly}\alpha}})^{0.5}(\frac{R}{100 \text{ pc}})^{-1.5}$ cm $^{-3}$, of which the ionization can be maintained by $\sim 10^4$ O5 stars as the ionizing source.

From the Ly α luminosity, we can estimate the star-formation rate (Thompson, Djorgovski, & Trauger 1995) to be $R_{\text{SF}} = (7 \pm 3) \text{ M}_\odot \text{ yr}^{-1}$, with both the internal and the Galactic extinction being corrected. This is consistent with the star forming rate given by Kulkarni et al. (1998) as a lower limit, $R_{\text{SF}} = 5.2 \text{ M}_\odot \text{ yr}^{-1}$ which was obtained from the rest-frame continuum luminosity at 1,500 Å.

3.2 Physical Configuration of the Supershell

We consider the dynamical evolutionary model of the supernova remnant to derive the physical quantities of the shell. According to Woltjer (1972), the supernova remnant has four evolutionary phases, that is, the free expansion

phase, the Sedov-Taylor or adiabatic phase, the snowplow or radiative phase, and finally the merging or dissipation phase (see also Reynolds 1988).

According to Woltjer(1972), the radiative phase begins roughly when the expansion velocity of the shell becomes

$$v = 300 \left(\frac{n_1}{1\text{cm}^{-3}} \right)^{2/17} \left(\frac{E}{10^{53} \text{ ergs}} \right)^{1/17} \text{ km s}^{-1}, \quad (3)$$

where n_1 is the number density of the ambient medium and E is the initial explosion energy. Since the expansion velocity $v = v_{\text{exp}} = 1500 \text{ km s}^{-1}$ of the supershell exceeds the velocity in the radiative phase by a large margin, we propose that the supershell is in the adiabatic phase, which is described by the Sedov solution.

According to the Sedov solution in a uniform medium of number density n_1 in which we have the relation $n_1 = 3N/R$,

$$R = 0.92 \left(\frac{E}{m_H N} \right)^{1/4} t^{1/2} \text{ cm}, \quad (4)$$

$$v = 0.37 \left(\frac{E}{m_H N} \right)^{1/4} t^{-1/2} \text{ cm s}^{-1}, \quad (5)$$

$$n_1 = 3.2 \left(\frac{m_H N^5}{E} \right)^{1/4} t^{-1/2} \text{ cm}^{-3}, \quad (6)$$

where v is the expansion velocity of the supershell, R the size of the supershell, E the initial explosion energy, N the column density of the supershell, m_H the hydrogen mass, and t the age of the shell.

Using the values $v = v_{\text{exp}} = 1500 \text{ km s}^{-1}$ and $N = 10^{20} \text{ cm}^{-2}$, we get

$$t = 4.7 \times 10^3 \left(\frac{E_{53}}{N_{20}} \right)^{1/2} \text{ yrs}, \quad (7)$$

$$R = 18 \left(\frac{E_{53}}{N_{20}} \right)^{1/2} \text{ pc}, \quad (8)$$

$$n_1 = 5.4 \left(\frac{N_{20}^3}{E_{53}} \right)^{1/2} \text{ cm}^{-3}, \quad (9)$$

where $N_{20} = N/10^{20} \text{ cm}^{-2}$ and $E_{53} = E/10^{53} \text{ ergs}$.

From these values we estimate the total kinetic energy of the expanding supershell given by $E_k = 2\pi R^2 N_{\text{HI}} m_H v_{\text{exp}}^2 = 7.3 \times 10^{52} E_{53} \text{ ergs}$. It is also

noticeable that this kinetic energy can be comparable to those of the galactic supershell including those in Our Galaxy, NGC 4631, and M101 (Heiles 1979, Rand & van der Hulst 1993, Wang 1999). Furthermore, the P-Cygni $\text{Ly}\alpha$ lines of the primeval galaxies also show the similar energy scale. Thus, we propose that the supershell can be the remnant of a hypernova or a GRB that had exploded earlier than GRB971214.

4 Summary and Implications

We have studied on the formation of P-Cygni type $\text{Ly}\alpha$ in the spectrum of the host-galaxy of GRB971214, and found that there are at least three components in the system, i.e. the parsec scale remnant of GRB971214 itself, a giant H II region, and a supershell surrounding it.

The giant H II region from which $\text{Ly}\alpha$ emission originates is photoionized by a super stellar cluster whose total ionizing photons correspond to those emitted from about 10^4 O5 stars. The existence of the P-Cygni type absorption plausibly implies that there exists a supershell surrounding the H II region. By a profile fitting procedure, we found out that the shell is expanding with a velocity of $v_{\text{exp}} = 1500 \text{ km s}^{-1}$ and its neutral column density $N_{\text{HI}} = 10^{20} \text{ cm}^{-2}$. We also revised the redshift of the $\text{Ly}\alpha$ emission source to be $z = 3.425$, and its unobscured $\text{Ly}\alpha$ luminosity to be $L_{\text{Ly}\alpha} = (1.8 \pm 0.8) \times 10^{42} \text{ erg s}^{-1}$, which gives a more reasonable star formation rate to be $R_{SF} = (7 \pm 3) \text{ M}_{\odot} \text{ yr}^{-1}$.

We also applied the theory on the hydrodynamical evolution of supernova remnants to the supershell surrounding GRB971214. Assuming a reasonable scale of the initial explosion energy of the supershell, we propose that the supershell is at the adiabatic phase, with its radius $R = 18 E_{53}^{1/2} \text{ pc}$, its age $t = 4.7 \times 10^3 E_{53}^{1/2} \text{ yrs}$, and the number density of the ambient medium $n_1 = 5.4 E_{53}^{-1/2} \text{ cm}^{-3}$, where $E_{53} = E/10^{53} \text{ ergs}$. And we estimate the kinetic energy of the supershell to be $E_k = 7.3 \times 10^{52} E_{53} \text{ ergs}$.

Recently one of the most debated suggestions is the hypernova conjecture, according to which gamma-ray bursts occur in star forming regions. Our results strongly favor this model and more concrete evidence is expected as the sample of GRB spectra showing $\text{Ly}\alpha$ emission becomes statistically significant. If gamma-ray bursts occur in star-forming region, then we can expect the density of ambient media is very large and exceeds $10 - 100 \text{ cm}^{-3}$. However, recent multi-wavelength analysis of selected gamma-ray burst afterglow by Panaitescu & Kumar (2001) have shown that the ambient density is as low as 10^{-1} to 10^{-3} cm^{-3} , and perhaps even less. Scalo & Wheeler (2001) argued that low ambient density regions naturally exist in areas of active star formation as the interior of superbubbles. This idea had been already presented in Ahn (1998),

where the observational evidence of pre-existing superbubble in the host galaxy of GRB971214.

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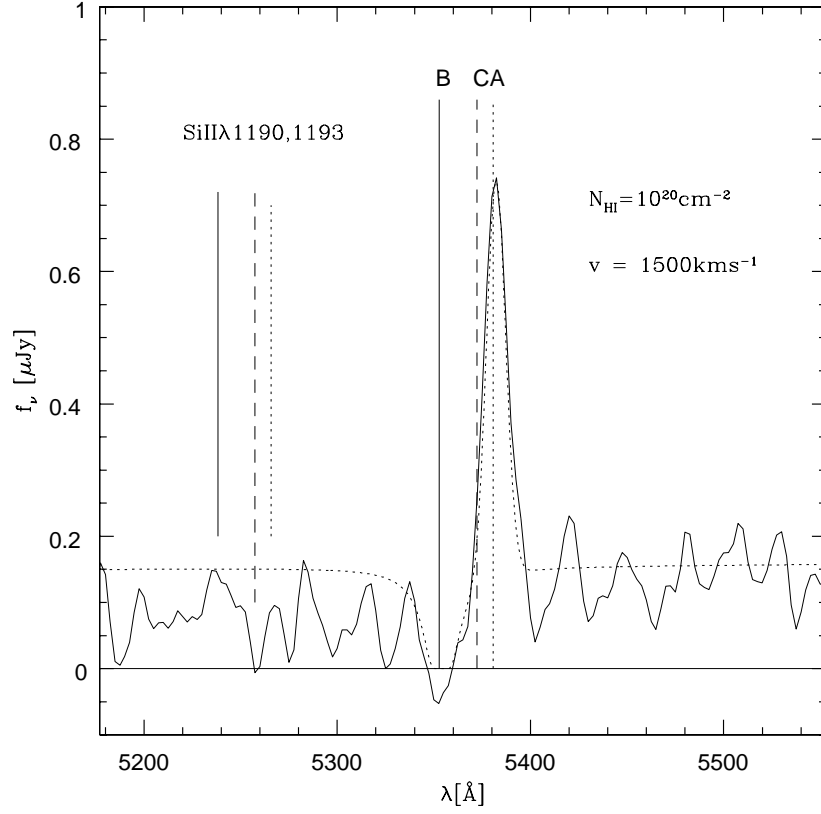


Figure 1: Profile of the Ly α emission line and its P-Cygni type absorption (solid line) with the best fit profile (dotted line). The emission has a Gaussian profile whose width is 5.0 Å, line center flux $f(\lambda = 5380.8 \text{ Å}) = 0.675 \text{ μJy}$. The line center frequency $\lambda = 5380.8 \text{ Å}$ gives $z = 3.425$. The P-Cygni type absorption is best fitted by the column density of the supershell $N_{\text{HI}} = 10^{20} \text{ cm}^{-2}$ and the expansion velocity $v_{\text{exp}} = 1500 \text{ km s}^{-1}$. The dotted vertical line denoted by 'A' is the solid line center of our result, the line denoted by B is the location of the P-Cygni absorption trough, and the 'C' vertical line is provided by Kulkarni et al. (1998). Comparing with Ly α we also show SiII λ 1190 line, but the S/N ratio is not good.